Title: JESD89 TEST STANDARD

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- This test standard is specifically for terrestrial radiation effects:
  - Wide range of neutron radiation effects
  - Alphas from packaging (why we don't do this for space, I don't know)

- In this talk, I am only covering the JESD89A (Revision of JESD89, August 2001) version of the test standard
  - This version was re-balloted in Oct 2006 without changes.
  - The JESD89B is at balloting right now. It is a major rewrite that took 5 years to complete. I will discuss some of the changes, but these changes are not in effect
  - Don't ask me why we increment by letter and not number, except there are three parts of the test standard

JESD89A PECULIARITIES

- Focuses almost exclusively on SEU.

- In 2006 were starting to see SEL at LANSCE, but so rare that it does not change the test standard.

- Rarely, if ever, seeing SETs or SEFIs at LANSCE

- All of this changes over the next decade. The terrestrial radiation effects community starts to see a wide range of SEEs
  - SEUs very easy to measure to statistical confidence quickly
  - SEL, SETs, and SEFIs are measureable but with a low statistical confidence
  - Neutrons become one of the easiest methods for measuring SEB and SEGR, due to no ranging issues.

- But all of that is not covered in JESD89A

TEST STANDARDS VS. TEST GUIDELINES

Test Standards

- Explain how to do repeatable and reproducible tests of the same DUT
  - The organization, the radiation source, and test setup may vary, but the results should be the same
- Develop standard methods for executing tests and reporting results
  - A common language for the test methodology
  - A common set of information in the test report
  - A list of facilities to use
- Concerned about testing at the highest level of abstraction
- It informs test design, but does not guide test design

Test Guidelines

- Concerned about testing of specific parts or family of parts
- Directly informs test design, but does not provide guidance on facilities or reporting
- We have several test guidelines that we will use this summer:
  - JPL Microprocessor Test Guideline and the SoC Test Guideline
  - LANL Microprocessor and FPGA Test Guidelines

OVERVIEW OF THE JESD89A

- Sections covered:
  - Test equipment and setup
  - Real-time (unaccelerated and high-altitude) test procedures
  - Accelerated alpha particle test procedure
  - Accelerated terrestrial cosmic ray test procedures
  - Accelerated thermal neutron test procedures

- Annexes
  - A (normative) Determination of terrestrial neutron flux
  - B (normative) Counting statistics
  - C (normative) Real-time testing statistics
  - D (informative) The alpha particle environment
  - E (informative) Neutron and proton test facilities
  - F Bibliographic References
  - G Differences Between JESD89A and JESD89

- What is the difference between a normative and informative annex?

DESIGNING TESTS

TEST EQUIPMENT

- The emphasis is on automated test equipment (ATE) both hardware and software
  - Unlike heavy ion and proton testing, neutron and alpha testers walk away from their tests all of the time (less true now)
  - Test needs to collect data autonomously and respond to test conditions robustly
    - Eric's work on recent tests has been automating our tests, including crash recovery for microcontrollers

- Suggested requirements of the ATE hardware:
  - 1) The ability to adjust and monitor the temperature of the DUT.
  - 2) Monitoring power supply current compliance to check for latchup.
  - 3) Operation at, or near, the rated DUT clock speed if test performed in dynamic mode.
  - 4) The ability to record particle fluence for each test if electronic data access from a detection system is provided by the test facility (this enables each test run to store the fluence with the data file).

TEST EQUIPMENT

- The ATE software should be capable of
  - 1) Controlling device initialization and rudimentary functional checks.
  - 2) Device operation in dynamic or static operation, as required by the test plan.
  - 3) Resetting the DUT during irradiation or real-time testing.
  - 4) Error detection and logging, including the time that the error was detected. It is important during error detection that new errors are not omitted or that corrections are made for system dead time.

- Also desirable
  - 1) Bit error mapping and data processing, storage and retrieval for display.
  - 2) Applicability to a variety of device types.
  - 3) High-speed operation and a high duty factor.
  - 4) Real-time DUT data display capability providing a higher test throughput and allowing for more precise control of testing.
  - 5) The ability to do preliminary data analysis while the test is in progress. This feature is desirable for modification / optimization of test procedures in light of the data being collected.
  - 6) Reliable audit path for data collection to allow correlation of experimental notes and collected data from the ATE.
  - 7) Recording the particle fluence, either automatically acquired from the test facility or manually entered.

THOUGHTS ON TEST EQUIPMENT

- Even if it is not ATE, the system is partitioned into
  - Hardware/Software
  - DUT/Instrumentation

- This is a framework for both thinking about the test design, but also test reporting

- Example:
  - Microprocessor test:
    - DUT microprocessor running test software -> in the beam
    - Instrumentation computer collecting and storing results -> out of the beam
    - ATE: would be nice to have equipment to monitor for hangs, crashes and change programs
  - Power MOSFET test:
    - DUT power MOSFET -> in the beam
    - Instrumentation equipment: programmable power supply and counter -> out of the beam
    - ATE: automated counting is necessary for this type of test

TEST CONDITIONS

- Static vs dynamic
  - An important aspect: static makes measuring some effects easier, but does not necessary indicate what the dynamic behavior would be like

- Test patterns: memory tests only, some microprocessors, on-line memory in an FPGA (but not configuration)

- Supply voltage

TEST FLOW

Figure 3.1 — Flow diagram comparing static and dynamic testing.
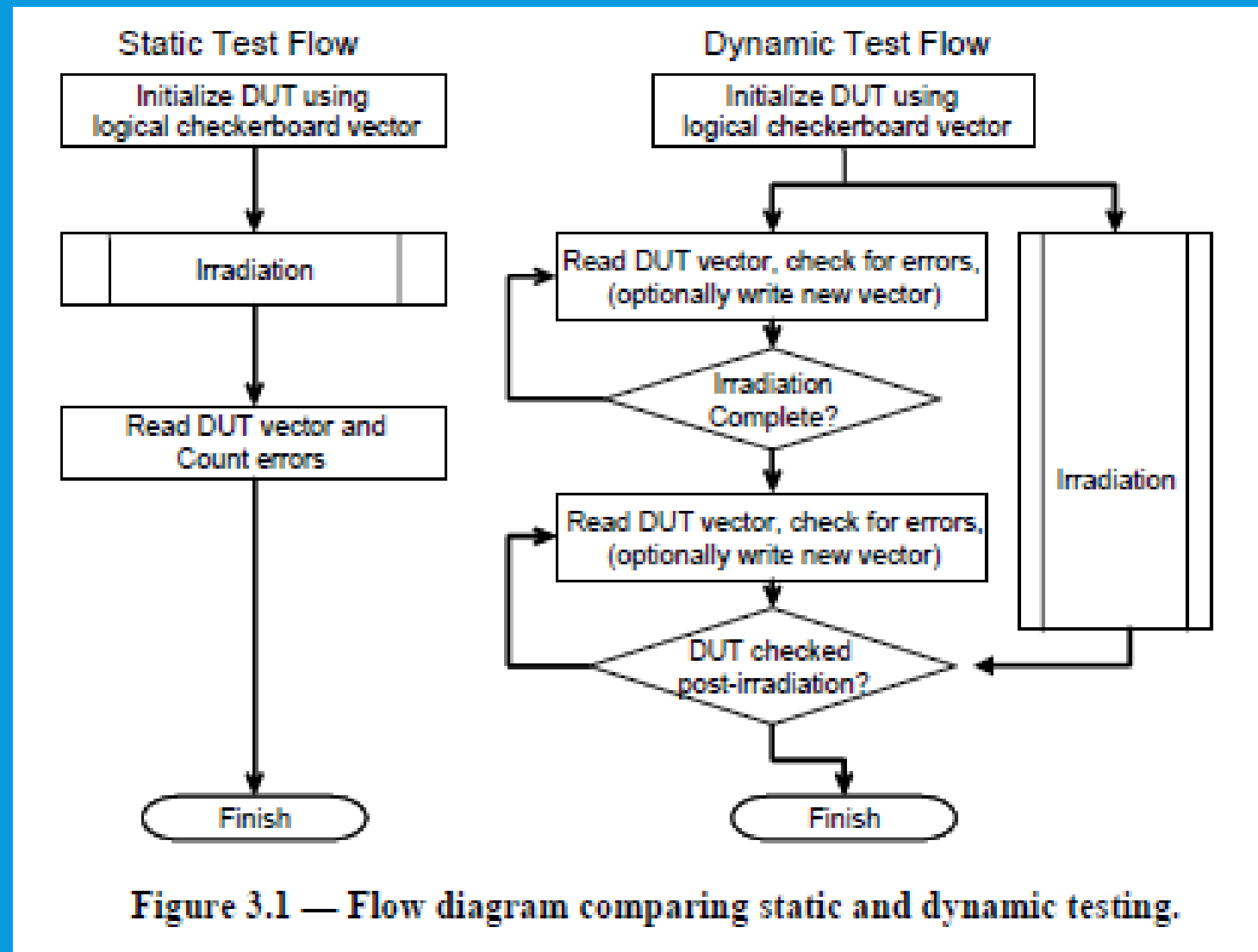
MINIMAL GUIDANCE FOR OTHER COMPONENTS

- Random logic

- Microprocessors

- FPGAs

- Check out the guidance for your part
    - It is likely not enough but it is the start of some thoughts on how to test your part
    - For real guidance, let's use our NASA and LANL resources

TYPES OF TESTING

- In this version, there is information about these types of tests:
  - Real-time system testing
  - Accelerated neutron testing
  - Alpha testing
  - Thermal neutron testing

DIFFERENT TYPES OF TESTS

STANDARD TO EACH TYPE OF TEST

- Each type of test has requirements for:
  - Test setup
  - DUT prep
  - Test execution
  - Final reports

REAL TIME TESTING

REAL-TIME SYSTEM TESTING?

- Just as it sounds:
  - Racks/arrays of DUTs and/or systems to do a life test
  - To some degree: our supercomputing clusters are real-time system tests

- A few manufacturers still do this type of testing:
  - Xilinx's Rosetta cluster

- Useful in the early days:
  - Testing in caves provided the ability to remove neutron upsets from the test, so alpha issues were isolated
  - LANSCE did not exist in the early days, so using mountainous locations was helpful

REAL-TIME TESTING

- Test issues:
  - Must be able to run the array remotely or with ATE for months, if not years
    - Backup power
    - Neutron flux monitors
    - Ability to maintain the hardware configuration
    - Ability to record and backup data
    - Ability to record date/time accurately

- DUT prep:
  - Possibly none
  - If the prep is "non-standard" might create system-specific effects

- Final report needs to include information about date/time of errors, location of the array, amount of time tested, etc.
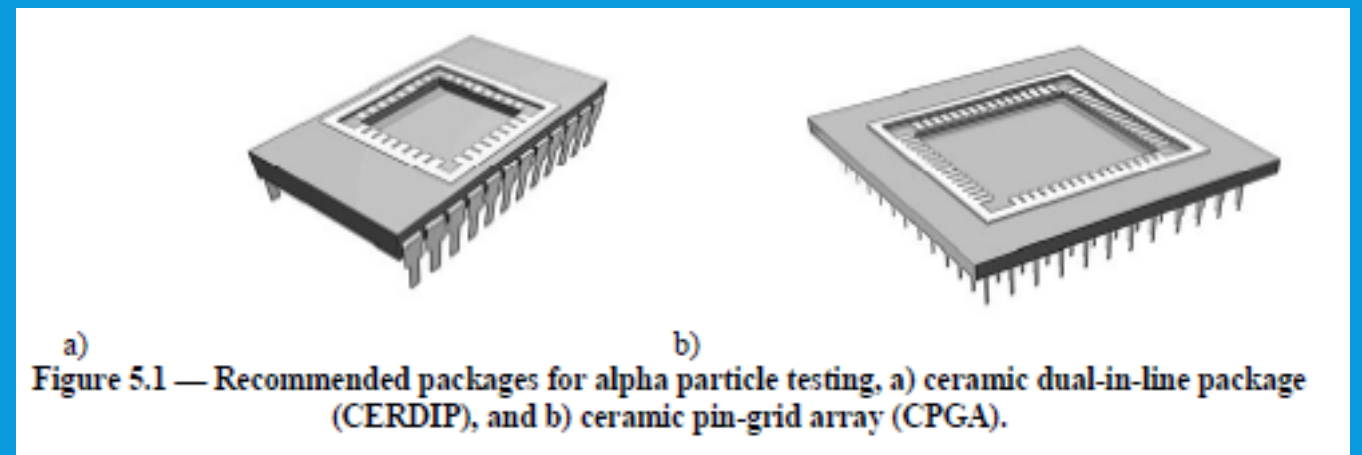
DIFFERENCES BETWEEN REAL-TIME TESTING AND ACCELERATED TESTING

- Geometry matters: are the components stacked horizontally or vertically?

- System effects:
  - Are errors masked by ECC?
  - Are there differences between the real system and the test system?

- Is the software overwriting errors before they are reported?

- Is the packaging different? Are there heat sinks?

ALPHA TESTING

ALPHA TESTING

- This is heavy ion testing, so many of the usual problems apply:
  - The DUTs need to be delidded and prepped
  - There could still be issues with range, and needing a vacuum

- The particle environment is covered in Annex D

a)   b)
Figure 5.1 — Recommended packages for alpha particle testing, a) ceramic dual-in-line package (CERDIP), and b) ceramic pin-grid array (CPGA).

ALPHA SOURCE SELECTION

- Generally, this is sealed source testing, although LBL does provide an accelerated alpha ion

- In sealed source testing, the radioactive source needs to be an alpha emitter:
  - Po210 is used to simulate solder bumps in flip chips

- There are a number of thin film alpha sources that might or might not be sealed sources
  - We have access to one that is sealed with a shutter, but there are issues with the range due to transmission in the air

- Discussion about fluence, test length and flux:
  - Want to test to a fluence to get statistical confidence
  - If the flux is too high, then accumulation of faults can be an issue

LOADING THE ALPHA SOURCE
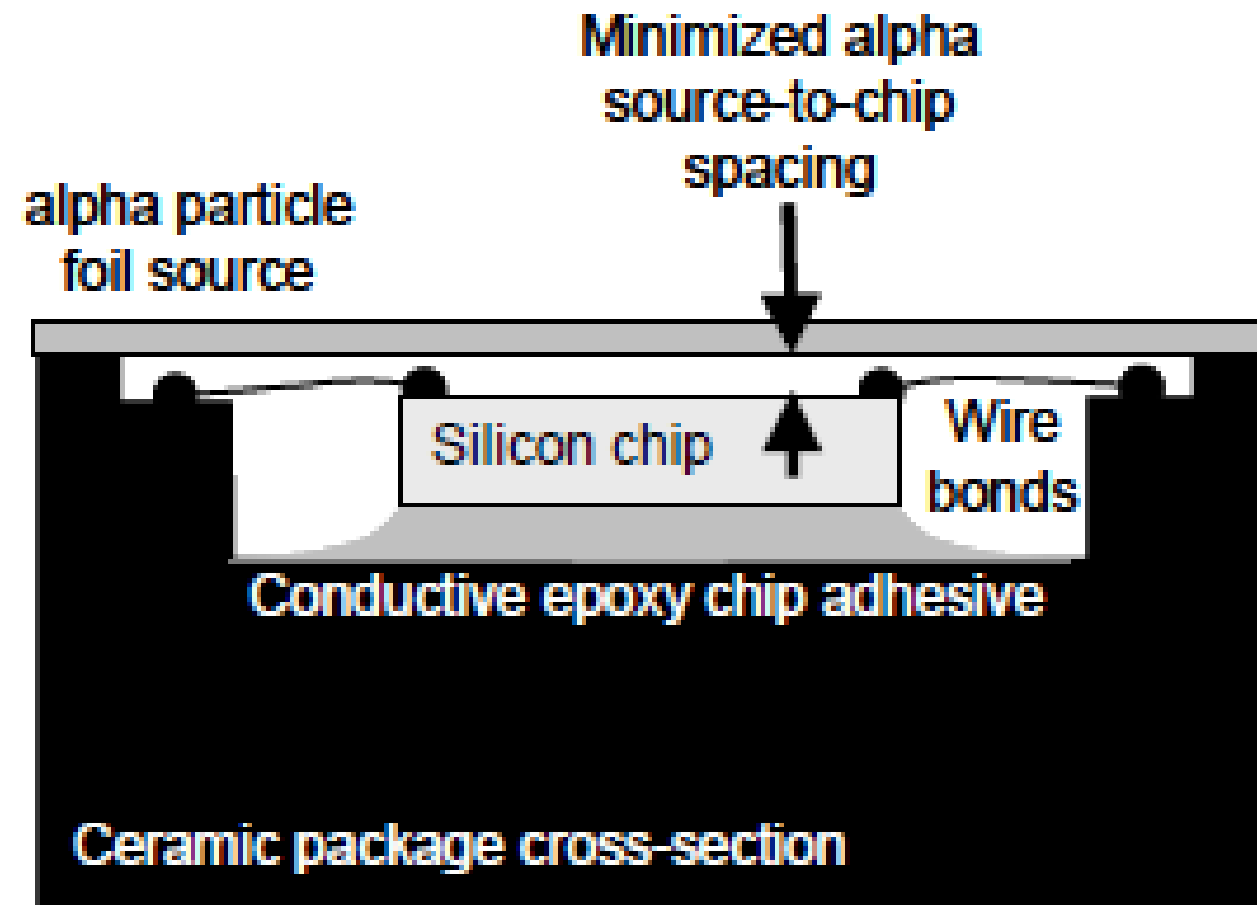
Figure 5.2 — Cross-section through ceramic package illustrating recommended alpha source size and placement – larger than the chip and as close to the chip as possible.

TESTING

$$Acceleration\ Factor = \frac{Alpha\ Particle\ Source\ Flux}{Packaged\ Component\ Alpha\ Flux} \sim 10^5\ to\ 10^{14}$$

- Test methodology:
  - Standard setup: load patterns, test, take data
  - Keep in mind the acceleration factor, which can be wide
  - Geometry of the system is a factor, too
  - Unlike neutron testing, total dose can be an issue
  - Unlike neutron testing, more SEL and SEFI problems

- Final report needs to include information about the source, the source-to-die spacing, estimated flux in the active volume, angle, SER calculation, etc.
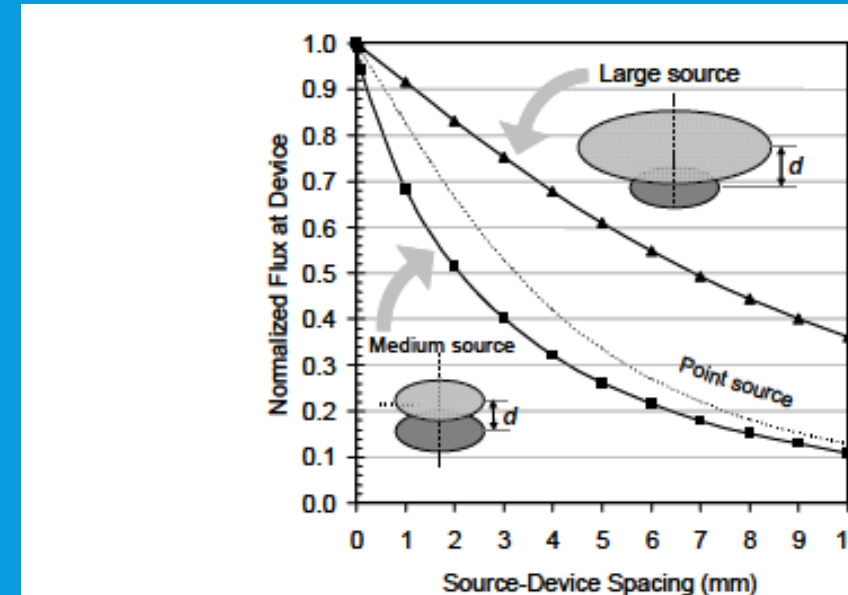

Figure 5.3 — Normalized alpha flux, averaged over the entire device area, incident on a device as a function of the source-device spacing and the source size.

PREDICTING ERROR RATES IN THE FIELD

- Need to extrapolate from the accelerated test results to use conditions

$$Unaccelerated\ Alpha\ Particle\ SER = \frac{(\Phi_{pkg}) \cdot (F_{geopkg}) \cdot (F_{shieldpkg})}{(\Phi_{dut}) \cdot (F_{geodut}) \cdot (F_{shielddut})} \cdot ASER \qquad (5.2)$$

- ASER is the soft error rate obtained from accelerated testing.

- Besides the flux components, there are also the F factors that based on the geometry of the DUT, the package, and the shielding
  - If the same metal-dielectric stack is used for testing and the final product then the shielding factors drop out

FAST NEUTRON TESTING

ACCELERATED COSMIC RAY TESTING

- This is the test guideline for testing at broad spectrum neutron sources
  - LANSCE
  - TRIUMF
  - ChipIR

- It is useful only for predicting the types of errors and the error rates seen from fast neutrons
  - This is strictly the (n, Si) reaction, not the (n, B10) reaction or the alpha reaction
  - These results cannot be used to predict the types of errors and error rates from the (n, B10) reaction or the alpha reaction

E_MIN

- There is an ongoing issue with E_min

- The JESD89A test standard defines E_min=10 MeV, which means
  - Even if the DUT's E_0 <10 MeV, the faults are counted but the fluence is not
  - Even if the DUT's E_0 > 10 MeV, the fluence is over counted

- At the heart of the problem, broad spectrum neutron sources do not provide information about E_0, so the test standard sets E_0 to 10 MeV unless E_0 is known.

- LANL research shows that 1-10 MeV proton cross sections do not predict 1-10 MeV neutron cross sections, so need to do mono-energetic neutron testing to determine the E_0

- LANL 2018 paper shows that there is not enough information to change E_min right now – maybe in the JESD89C

TEST FACILITIES

- While the standard methodology is testing in white sources, the standard also suggests the use of "quasi-monoo-energectic" neutron sources and protons

- Why protons?
  - There is some research that shows that the (n, Si) and (p, Si) reaction above 50 MeV are roughly the same
    - That turns out to be more complicated, but we need someone to study the problem to provide better judgement
  - Proton testing is faster due to higher fluxes, and easier to get energy-dependent cross sections. Can get more data faster to help influence the design cycle.
  - What we find with the manufacturers is that they will test extensively in protons until they are ready to publish results. Then they will test in white neutron source, and publish those results

USING MONO-ENERGETIC SOURCES

- For both protons and neutrons trying to drive to same value: energy-dependent cross sections

and
$$\sigma_{SEU\text{-}dev}(E_p) = N_{SEU} / (\Phi_{proton}) \tag{6.1}$$
$$\sigma_{SEU\text{-}bit}(E_p) = N_{SEU} / (\Phi_{proton} \times N_{bit}) \tag{6.2}$$

and
$$\sigma_{SEU\text{-}dev}(E_n) = N_{SEU} / (\Phi_{neutron}) \tag{6.3}$$
$$\sigma_{SEU\text{-}bit}(E_n) = N_{SEU} / (\Phi_{neutron} \times N_{bit}) \tag{6.4}$$

- In both cases, the test must be able to measure the number of errors and the amount of fluence

- Some slight differences in quasi-mono-energetic sources:

and
$$\sigma_{SEU\text{-}dev}(E_n) = N^*_{SEU} / (\Phi_{neutron}) \tag{6.5}$$
$$\sigma_{SEU\text{-}bit}(E_n) = N^*_{SEU} / (\Phi_{neutron} \times N_{bit}) \tag{6.6}$$

  - Need to figure out how many errors occurred at the peak energy

SPALLATION SOURCES [FROM THE JESD89A]

- "Spallation neutron sources measure the SEU rate and derive an *averaged* SEU cross section. Because the neutrons produced from a spallation source cover a wide energy spectrum, the user cannot extract a SEU cross section at a specific energy from such measurements, but rather obtains the contribution of SEU events from neutrons of all energies within the spectrum. The major reason that a spallation neutron source is widely used is that the shape of the energy spectrum from this beam is similar to the spectrum of the terrestrial neutrons on the ground and in the atmosphere [11]."

- In other words: each facility is only as good as its ability to match the terrestrial radiation environment
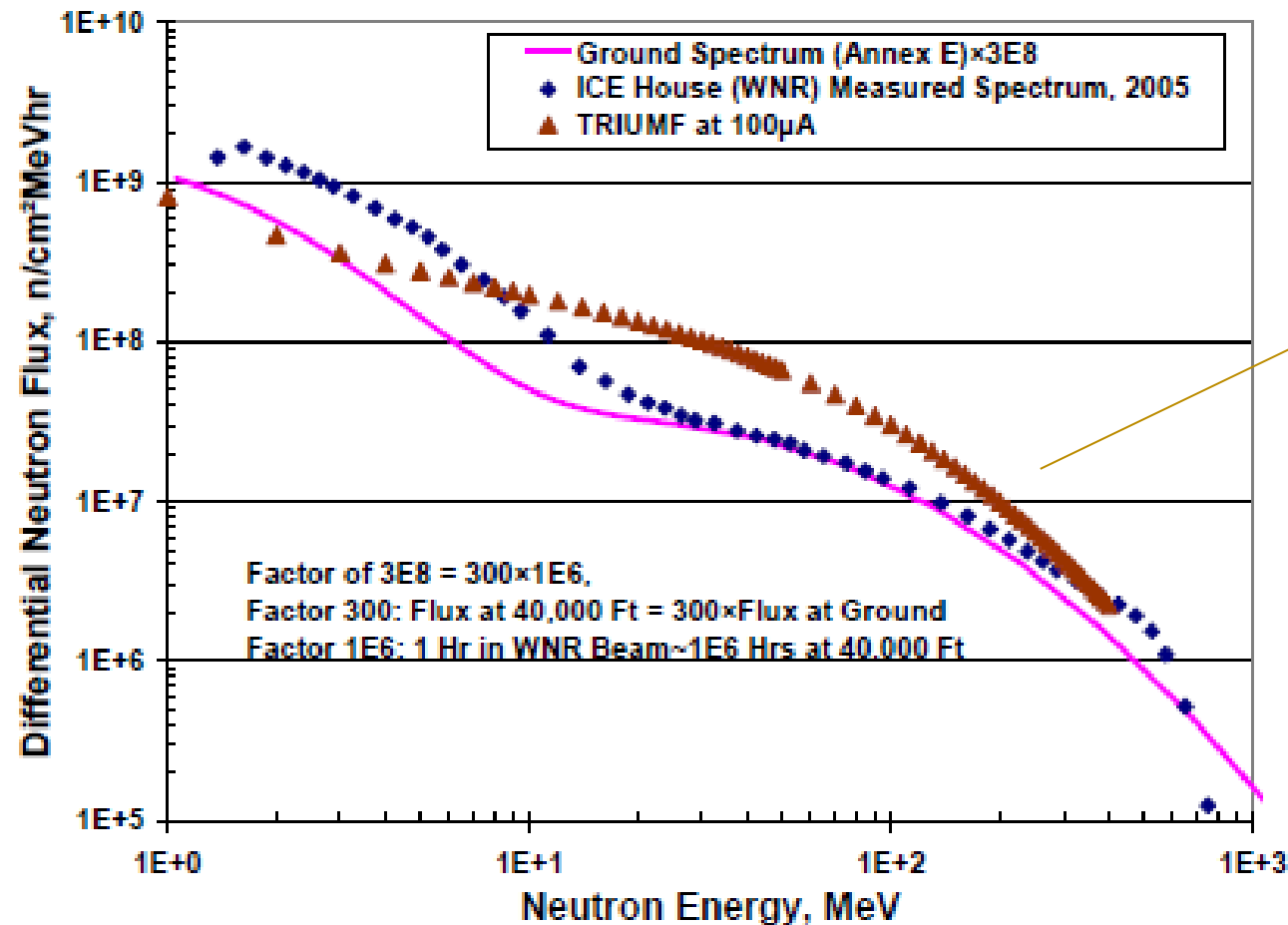
COMPARISONS

Figure 6.1 — Comparison of Los Alamos and TRIUMF neutron beam spectra with terrestrial neutron spectrum from annex A.

Neither are perfect: the LANSCE spectrum has too many 1-10 MeV neutrons, and TRIUMF has too many 10-100 MeV neutrons, and each facility has its own E_max. Surprisingly, this only creates about a 2x error in the SER

ANOTHER RUN AT E_MIN

- Part of the reason why E_min is important is that in 2006 there were very few parts with an E_0 < 10 MeV. It was more common that E_0 was > 10 MeV.

- On top of it, all of the facilities are off a bit. It is kind of self-correcting, especially if you test at both LANSCE and TRIUMF because one is too high and the other too low by about the same amount.

- These are fundamental assumptions that need to be studied before the JESD89C rewrite

SPALLATION CROSS SECTIONS

- One thing we don't see a lot of: the fact that this is specified as an average

$$\overline{\sigma_{SEU-dev}} = N_{SEU} / \Phi_{spec} \tag{6.7}$$

and

$$\overline{\sigma_{SEU-bit}} = N_{SEU} / \left(\Phi_{spec} \times N_{bit} \right) \tag{6.8}$$

- The events are counted "as is" as it is not possible to correct for E_0 and E_min being different

- The fluence is counted from 10 MeV and up
  - LANSCE gives you both >= 10 MeV and >= 1.5 MeV, but no one is using the second number.
  - The standard states that only >= 10 MeV is necessary
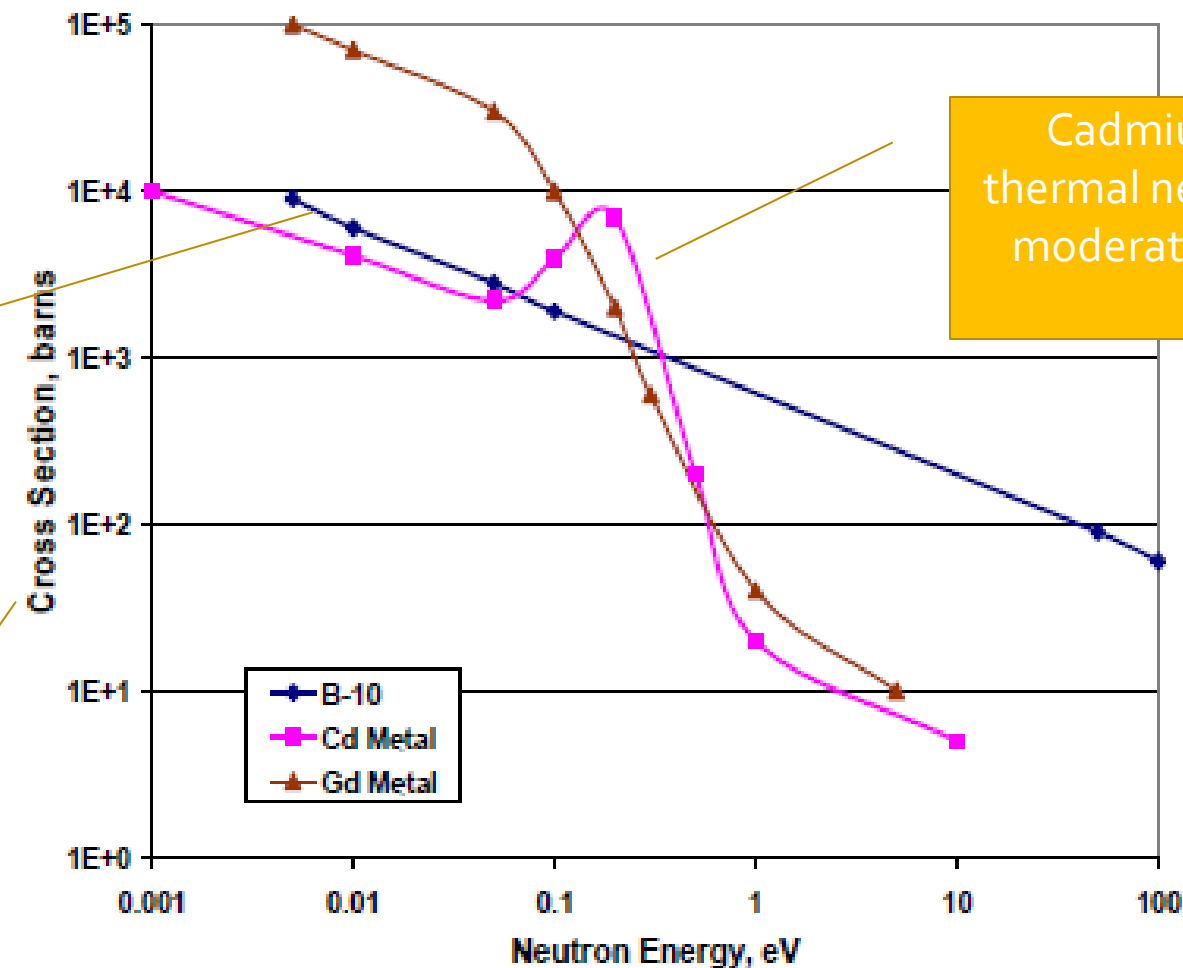
THERMAL NEUTRON TESTING

THERMAL NEUTRON TESTING

- This one keeps flip flopping on the test community: some parts have B10 and some do not
  - What LANL is finding is that there is a measureability issue, too.
  - Some parts have B10, but the cross section is unmeasureable given the limits of beam time.

- Fundamentally, similar to accelerated fast neutron testing, except
  - Measure with and without a shield to remove the thermal neutrons because the sources are not mono-energetic
  - Facilities are different and varied: further study needed on the effect of the facility on the test measurement

WHY THE SHIELD?

Figure 7.1 — Variation of the thermal neutron cross section with energy for B, Cd and Gd

Why you should avoid cold neutron beam lines

Note: different type of cross section!

Cadmium moderates the thermal neutrons, but does not moderate the higher energy neutrons

SHIELDING THICKNESS MATTERS

Table 7.1 — Neutron attenuation as a function of thickness for various materials

Shield Thickness, mm	Boron (^{10}B)	Cadmium (^{113}Cd)	Gadolinium (^{157}Gd)
.01	9.1E-1	8.9E-1	3E-1
.1	3.7E-1	3.1E-1	5.8E-6
1	4.7E-5	8.8E-6	4.3E-53

Recommended

THERMAL NEUTRON CROSS SECTIONS

- If the source really does give only thermal neutrons, then we could do the standard events/fluence

- Unfortunately, that is rarely true, so we use the subtraction method:
  - $\sigma_{total} - \sigma_{shielded}$

- There are issues, though:
  - Testing time is limited, and getting statistical significance might not be possible
  - It could be that the two values are approximately the same, and you end up with an engineering zero
  - One or both cross sections could be a null, which makes it even more complicated

- There is a real measurement issue in the heart of this calculation that has not been solved:
  - Beth's NSREC paper looks at using something of a "bootstrap" method

CONCLUSIONS

- The JESD89 test standard provides guidance on:
  - Proton
  - Fast neutron
  - Thermal neutron
  - Alpha testing

- The test standard provides a methodology for repeatable and reproducible testing
  - Some of this is on the radiation testers – must provide enough information about the test so that others can reproduce it!